Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 51-1 (2018) 627–632

Attitude Control Schemes for Crew Module Atmospheric Re-entry Experiment Mission

N.Soumya, Asha.P.Nair, V.Brinda, D.S.Sheela V.R.Lalithambika, M.V.Dhekane

Control Guidance and Simulation Entity, Vikram Sarabhai Space Centre, Thiruvananthapuram, 695022, India (e-mail: soumyan48@gmail.com, ashaparvathi@gmail.com)

Abstract: The Crew Module Atmospheric Re-entry Experiment mission is a suborbital mission of flying Crew Module (CM) as the payload in a parent launch vehicle. After separation from the launcher, Crew Module (CM) performs suborbital re-entry flight from an altitude of 126 km. The module is actively controlled from the instant of its separation from the launcher up to the point of re-entry into the atmosphere at 80 km after which it follows a ballistic flight through the atmosphere. Three axis control with Reaction Control System (RCS) is envisaged during exo atmospheric descent to damp out the rates and ensure near zero degree angle of attack at re-entry. This paper gives different attitude control schemes proposed for the mission using RCS thrusters. The control strategy is based on proportional derivative controller with a modulator. The design techniques for different modulation schemes are discussed. Simulations results of crew module attitude control are also presented to demonstrate the obtainable performances from different modulation schemes.

Keywords: Attitude control, Reaction Control System, Pulse Width Modulation, Pulse Width and Pulse Frequency modulation

1. INTRODUCTION

Crew Module Atmospheric Re-entry Experiment mission is a suborbital mission in which Crew Module was carried as a payload in a launcher and it performed a flawless atmospheric re-entry flight till touch down [Ref.6]. Basic configuration of the crew module is given in Fig.1. The configuration is monostable or in other words has a single stable trim point. Monostability ensures that the crew module aligns itself to the desired trim attitude irrespective of the initial attitude given sufficient time [Ref-2]. One of the objectives of the mission was the demonstration of hypersonic mono stability of CM. Though it was a suborbital flight, this mission also provided opportunity to study the aero-thermodynamic environments on the crew module during its entry into atmosphere ranging from hypersonic regime to subsonic regime. Performance evaluation of deceleration systems also was targeted and successfully demonstrated.

Axis Definition The vehicle axes system is a right handed triad with origin at the centre of gravity of the vehicle. Rotation about the positive vehicle axes are positive attitudes. Positive pitch rate is the rate about the positive pitch axis, i.e, pitch down (from ZB axis towards XB axis) is positive. While looking from CM base clockwise roll is positive (Rotation about ZB). Similarly rotation about XB axis is yawing.

Mission Profile Typical mission profile is shown in Fig. 2. There are two distinct phases of CM mission after separation from the launcher.

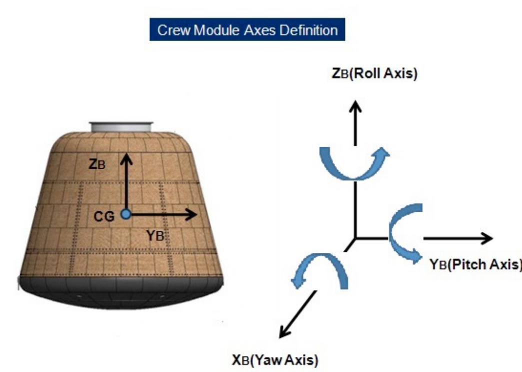

Fig. 1. Crew Module Configuration and Axis Definition

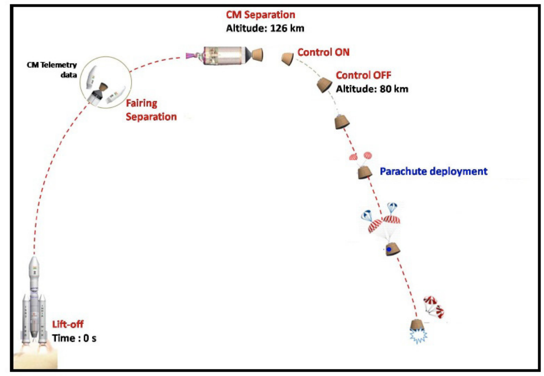

Fig. 2. Mission Profile

10.1016/j.ifacol.2018.05.105

Phase-1 (Controlled Phase) This exo-atmospheric phase begins at the point of stage separation and extends up to the CM entering the sensible atmosphere. RCS thrusters are exercised for control in crew module during phase-1 after separation. There are six thrusters available for CM attitude control, two each for pitch, yaw and roll control.

Phase-2 (Uncontrolled Phase) The atmospheric phase of flight begins with CM entering atmosphere and ends with its splashdown in sea. After atmospheric entry CM follows a ballistic flight through the atmosphere. Towards the end of atmospheric phase, parachutes are deployed to reduce the impact velocity of the module to acceptable limits. The module is not actively controlled during this phase. Control during atmospheric regime also was studied but was not flown in the experiment.

For attitude control, the capsule is provided with six numbers of 100 N thrusters. RCS thrusters have only two operating states:on and off implying it produces either a constant force or null force. To design a controller of such non linear actuators, either nonlinear algorithms must be developed or the control command is to be modulated to pulses. Modulating technique could be either pulse width, pulse frequency, or both the pulse width and frequency. These modulation techniques allow linear control laws like Proportional Derivative(PD) and Proportional Integral Derivative (PID) to applied to nonlinear systems.

1.1 Outline

The paper is organized as follows: Section 2 discusses the re-entry trajectory modelling. Section 3 gives the challenges and requirements in control law design. Attitude Control Schemes are explained in Section 4. Section 4 also gives design procedure and static characteristics of each modulation scheme. Simulation results are also included in section 4. The paper is concluded in Section 5.

2. CREW MODULE RE-ENTRY SIMULATION STUDIES

The planar equations of motion governing re-entry into the atmosphere are as follows. This description of the motion assumes the capsule movement to be planar, aerodynamic derivatives are assumed to be independent of mach number and show a linear variation with respect to angle of attack, small L/D of the capsule, small angles of attack, constant acceleration due to gravity, spherical non rotating earth, a rigid capsule with constant mass, and no atmospheric winds [Ref-1].

2.1 Planar Motion Re-Entry Trajectory Equations

$$\dot{h} = V sin(\gamma) \tag{1}$$

$$\dot{V} = \frac{-\rho V^2 C_D A}{m} - g sin(\gamma) \tag{2}$$

$$\dot{\gamma} = \frac{\rho V C_L A}{2m} - (\frac{g}{V} - \frac{V}{R}) sin(\gamma) \tag{3}$$

$$\ddot{\theta} = \frac{\rho V^2 AD}{2I}(C_{mq}\frac{\dot{\theta}D}{2V} + (C_{m\dot{\alpha}}\frac{\dot{\alpha}D}{2V} + C_{m\alpha}\alpha) \tag{4}$$

$$\theta = \alpha + \gamma \tag{5}$$

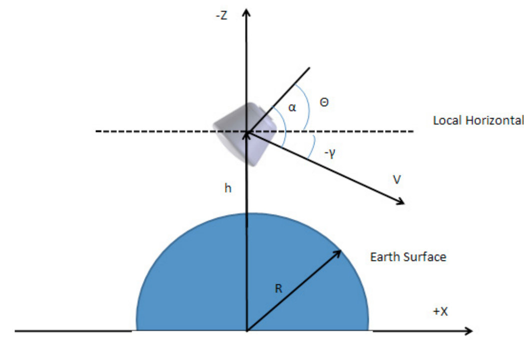

Fig. 3. Coordinate System [Ref-1]

3. CHALLENGES AND REQUIREMENTS IN CONTROL DESIGN

The static and dynamic stability of the crew module depends on aerodynamic moments acting on the vehicle which keep varying during hypersonic, supersonic and subsonic flight. The crew module though statically stable is dynamically unstable. A comprehensive investigation on blunt body dynamic stability is presented in Ref 1. The pitch damping derivative is often considered indicative of the dynamic stability -negative values indicating favourable response. Dynamic instability tends to start near low supersonic mach and becomes more unstable with decreasing mach number. Using the damping coefficient behaviour obtained experimentally, the oscillation amplitude history as the vehicle decelerates is plotted as a function of time [Fig 4]

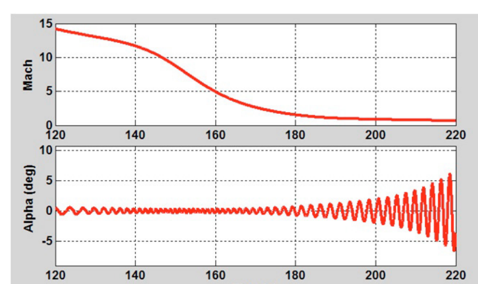

Fig. 4. Dynamic Instability- Oscillation amplitude history

Instability can cause blunt-body oscillations to grow so much that a safe parachute deployment is not possible and in extreme cases, dynamic instability can even result in very high rates. From control systems point of view, this instability may viewed as a pole on right half plane. When a control design through pole placement is carried out, the controller is designed such that the closed loop poles are on the left half. The open loop and closed loop pole locations are compared [Fig 5]. But such a scheme is feasible only if control till parachute deployment is planned.

Body rates at parachute deployment depend on angle of attack and rates at entry of sensible atmosphere. Parachute deployment condition cannot be met when the body rate at atmospheric entry exceeds 0.5 deg/s and angle of attack exceeds 1 deg. This dictates a stringent requirement on control scheme at control-off which is also the beginning of atmospheric reentry.

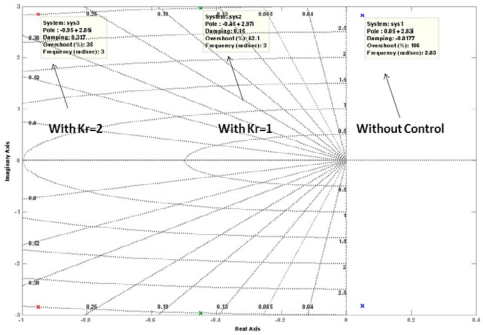

Fig. 5. Open loop and Closed loop pole locations

4. ATTITUDE CONTROL SCHEMES

In order to meet the stringent requirements at reentry, a navigation, guidance and control scheme was implemented for Crew Module flight. The NGC system performs several key functions prior to atmospheric entry. The attitude is represented as quaternion which is a basically a four parameter representation of attitude. Guidance commands are also expressed as quaternion. Based on the full navigation solution available guidance module computes the commanded quaternions. Quaternion errors are computed and approximated as body errors in pitch, yaw and roll. Closed loop guidance ensures that the module achieves near zero angle of attack at the re-entry. On sensing crew module separation from launch vehicle control is initiated. Control is required to track the commanded attitudes/quaternions and also to damp out the body rates to the acceptable levels.

A simulink based model which incorporates crew module dynamics and control law was developed. The external forces acting on the module are aerodynamics,gravity and RCS control forces and external moments are due to aerodynamics and RCS control moments. While simulating 3-DOF rotational dynamics,control coupling through RCS firings are also considered(CG-offset effects leading to cross axis disturbance). The moment created on the module by each RCS thruster is given by $M = r \times F$, where M is the moment, r the Position vector from CG to RCS mounting location and F is the thrust level of RCS thruster. Atmospheric effects such as winds are not modeled. Effect of interaction of RCS jet with aerodynamics are neglected as RCS is fired only during exo atmospheric flight. An initial condition is set in rates and errors. Simulations are extended till parachute deployment and rates and angle of attack at parachute deployment monitored. Simulations were also performed with dipsersions in Centre of Gravity(CG), Moment of Inertia (MI), RCS thrust levels and aerodynamic coefficients. Robustness of the control scheme with respect to the conditions at reentry is assessed and found satisfactory.Thrusters are operated in ON-OFF mode. Two types of modulation schemes studied for thruster system are discusssed in this paper. The first one is pulse width modulation (PWM) and the other is pulse width and pulse frequency modulation (PWPFM).

4.1 Pulse Width Modulation- On modulation

Pulse width modulation is the widely used modulation scheme for thruster control due to its simplicity. During on modulation scheme of operation thrusters are used for control purpose alone and when control is required, the appropriate thruster is switched ON. A firing command is given to the actuation system during every sampling period. RCS chattering can occur in any on-off control system in presence of sensor noise or high frequency excitation whenever the error function dwells near the dead zone boundary. Hence it is desirable to put a hysteresis in the forward path to have good RCS system performance. The control law adopted for crew module is given in Fig-6. The feedback variables are attitude angle and rate. Rate feedback provides damping to the system. K_A and K_R are forward and rate path gains respectively. Rate control logic (RCL) refers to a limit on attitude error. It is a simple logic which helps to clamp rates and also to save fuel.

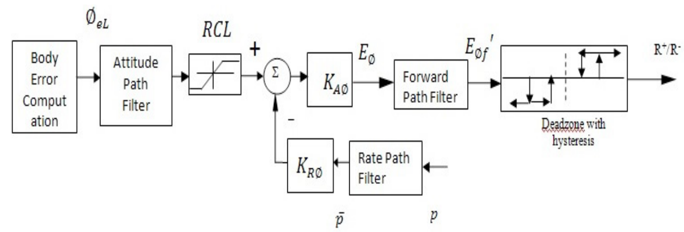

Fig. 6. Block schematic of PWM thruster control scheme.

Three different zones of operation were identified and design numbers were tuned to meet the requirements of each zone.

Zone-1 (Rate Capture) Control from final stage of launcher is put off five seconds prior to crew module separation. Separation event can impart rates as large as 2deg/s. At control ON large initial conditions(rates and errors) are expected due to separation disturbance and the error build up during no-control zone. During this zone guidance commands are zero and initial rates and errors are allowed to settle. Maneuvers are avoided to off load the actuation system. Error function for Rate capture control law

$$e_\theta = -K_{A\theta} K_{R\theta} q \tag{6}$$

Zone-2 (Reorientation phase) After capture of initial conditions guidance starts issuing attitude reorientation commands. During this zone commanded rates upto 2 deg/s are expected.During this zone RCL and dead zone values are relaxed to the meet the tracking requirements. Error function is modified appropriately as

$$e_\theta = K_{A\theta}(\theta_{EL} - K_{R\theta} q) \tag{7}$$

Zone-3 (Attitude and Rate phase) After reorientation manoeuvres guidance issues a command to maintain the capsule orientation to the desired value. During this zone the gains , RCL and dead zone values are tightened to meet the requirements at control -OFF. Error function remains same as zone-2 which is given by

$$e_\theta = K_{A\theta}(\theta_{EL} - K_{R\theta} q) \tag{8}$$

A detailed discussion on design of on-off control systems can be found in Ref 5. The on-off system will be subject to self sustained oscillations called limit cyles which appears as a closed path in phase plane analysis. Based on the

vehicle data (inertia and moment arm), thruster characteristics (ON/OFF controllers thrust level, on-off and rise-fall delays) and disturbance moment data, the performance curves for limit cycle frequency and maximum attitude error with respect to design parameters, dead zone and rate gains are derived [Fig 7]. The rigid-body limit-cycling characteristics of the system without any disturbance are summarised as follows [Ref-5]

Maximum Rate

$$\dot{\theta}1 = \frac{\alpha_c T_D (K_R - T_D/2)}{2K_R - T_R - T_D} \tag{9}$$

Maximum Amplitude

$$(-\theta_c + \theta_1)_{max} = (-\theta_c + \theta_1) + \frac{\theta 1^2}{2\alpha_c} \tag{10}$$

Thruster On time

$$T_{on} = 4\frac{\dot{\theta}_1}{\alpha_c} \tag{11}$$

Thruster Off time

$$T_{off} = 4\frac{\theta_1}{\dot{\theta}_1} \tag{12}$$

Time period

$$T_p = 4\left[\frac{\dot{\theta}1}{\alpha_c} + \frac{\theta}{\dot{\theta}}\right] \tag{13}$$

Percentage On Time

$$100\frac{T_{on}}{T_p} = 400\frac{\dot{\theta}_1/\alpha_c}{T_p} \tag{14}$$

Impulse consumption per second

$$I_s = \frac{OnTime \times Force}{Period} \tag{15}$$

where T_R is the equivalent on delay, T_D is the equivalent cutoff delay, $\alpha_c = M_c/I$ = angular acceleration due to control thruster, M_c being the control moment and I is the inertia of the module. From the expression for T_{on} it may be noted that the pulse width depends on inertia and thrust level and hence is varying.

The design charts derived using above expressions is given in fig 7. From the design charts it is evident that the maximum rate of limit cycle depends on K_R and is independent of the dead zone. As K_R is increased limit cycling rate decreases. Amplitude of limit cycle varies linearly with the dead zone. It can be seen that the frequency and therefore the impulse consumption varies inversely with dead zone. Initial design numbers for each zone were chosen based on design charts and finalised through simulations.Thrusters for attitude control being placed in a skewed and unbalanced manner, there will be cross axis disturbance. The disturbance and rates imparted are quantified analytically and through simulations. Typical simulation results are shown in Fig 8. The rate build up towards the end of simulations is due to the dynamic instability discussed in section 3. Benign initial conditions are ensured at atmospheric reentry with active control during exo atmospheric phase. It puts a limit on the maximum rate build up due to dynamic instability. In the results shown in Fig 8, pitch rate build up is less than 10 deg/s. Pitch attitude angle changes due to change of flight path angle. Also roll attitude is seen to increase after control off but is not of much concern as roll rate is well within 1 deg/s.

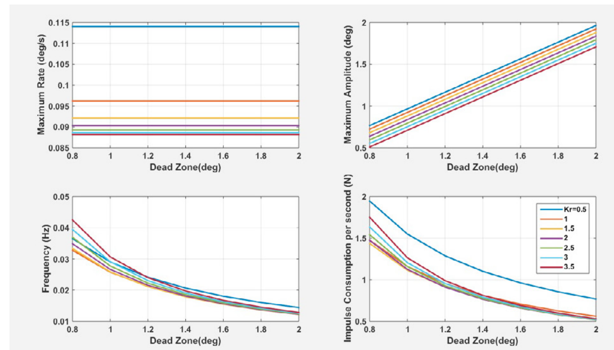

Fig. 7. RCS Design charts showcasing limit cycle characteristics

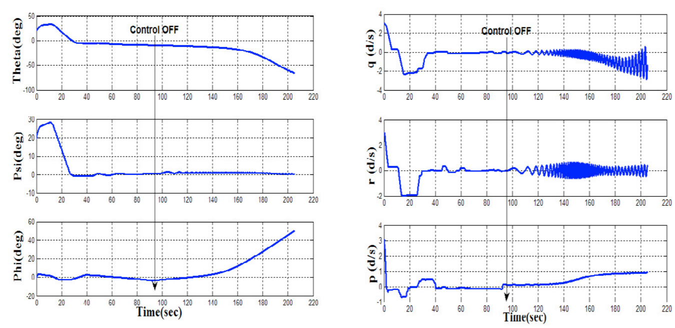

Fig. 8. Pitch Channel Control With PWM On Modulation-Attitude Angles and Rates

4.2 Pulse Width Modulation- Off modulation

Feasibility of using RCS thrusters for CM Maneuver to prevent collision with spent fragments was explored. Pitch thrusters were to be fired continuously to generate the required acceleration to move laterally away and prevent hitting the debris. Here the pitch thrusters are fired continuously to generate the required lateral drift. Based on this requirement to fire pitch thrusters continuously, feasibility of attitude control in pitch through OFF modulation was studied. Both pitch thrusters are always ON. In order to meet the control requirements, the opposite thruster is switched off (P- switched off when P+ requirement arises and vice versa).Yaw/Roll thrusters continue to be operated in normal mode (On modulation). Implementation is similar to block diagram shown in Fig 6. Only the firing logic gets modified

Attitude control through OFF modulation of pitch thrusters is a feasible scheme. Attitude follows the reference attitude. Errors and rates at control-off are less than 1 deg and 0.5 deg/s respectively which meets the mission specification. Preflight simulation predictions of pitch RCS firings along with the moment generated from firings as shown in fig 9. Small spikes visible in moments are due to

cross axis disturbance generated from firing of thruters for yaw/roll control purpose.Unbalanced thruster placement of pitch thrusters leads to difference between P+ and P- control moments. During continuous firing moment imbalance results in one directional attitude build up .For attitude control only pitch+ thruster is switched OFF frequently with 32 percentage duty cycle while pitch- thruster is continuously firing. This is due to the lower control moment of Pitch- thruster. This can result in continuous firing for long duration and high fuel requirement.

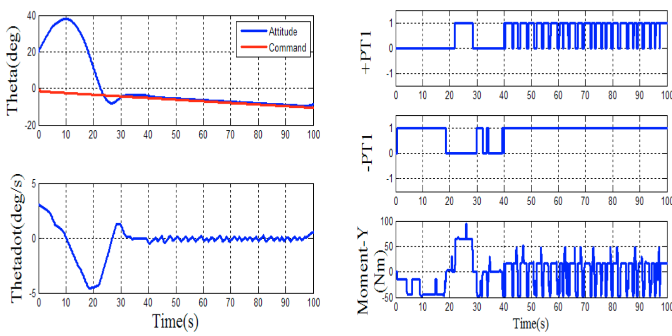

Fig. 9. Pitch Channel Control With Off Modulation

4.3 *Pulse Width and Pulse Frequency Modulation*

The pulse-width pulse-frequency modulator (PWPFM) is widely used for spacecraft attitude control. Pulse-width pulse-frequency modulation scheme modulates both the width of pulses and the distance between them and provides a pseudolinear operation for an on-off thruster[Ref-3,7]. Compared to PWM scheme, PWPFM scheme can generate smaller commanded pulses. The PWPF modulator has the advantages like high accuracy and adjustable pulse width and pulse frequency and also results in reduced fuel consumption. PWPFM modulator is used with the existing PD control law. PD control parameters, and modulator parameters determine the amplitude and rate of the rigid body limit cycle. Output of the PWPFM is given to a thruster selection logic. Modulator comprises chiefly two components: a first order lag filter and a Schmitt trigger inside a feed back loop. The filter integrates the error signal and when the integrated output reaches the threshold, the schmitt trigger switches on and turns on the thruster. This discharges the filter and when it reaches the lower threshold of schmitt trigger, the thruster again turns OFF. Parameters of the PWPFM is designed to have a minimum pulse width.

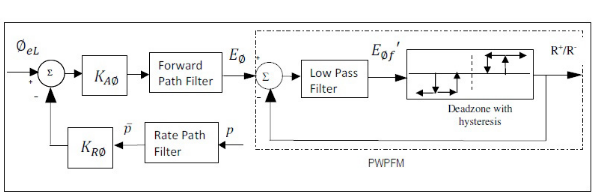

Fig. 10. Generation of RCS Firing Commands with PW-PFM Modulator

Modulator Static Analysis The modulator behavior is independent of the system in which it is used. Compared to the system dynamics modulator characteristics change at a much faster pace. Hence the input to the modulator is a slowly varying quantity and behaviour of modulator with constant input gives a good indication of modulator performance[Ref 10]. The static characteristics of the PWPF modulator are given by [Ref 9]:

Thruster on time

$$T_{on} = -T_m ln\left\{\frac{(1-h)E_d - (E-1)}{E_d - (E-1)}\right\} \tag{16}$$

Thruster off time

$$T_{off} = -T_m ln\left\{\frac{E_d - E}{(1-h)E_d - E}\right\} \tag{17}$$

Frequency of limit cycle

$$f = \frac{1}{T_{on} + T_{off}} \tag{18}$$

Duty Cycle

$$DC = \frac{T_{on}}{T_{on} + T_{off}} \tag{19}$$

Internal Dead Zone

$$dz = \frac{U_{on}}{K_m} \tag{20}$$

Saturation Level

$$sat = 1 + \frac{U_{off}}{K_m} \tag{21}$$

Minimum Pulse Width

$$\Delta = -T_m ln(1 - \frac{h}{K_m}) \approx \frac{hT_m}{K_m} \tag{22}$$

where E the static input magnitude, U_{on} and U_{off} are schmitt trigger parameters (when positive input to the schmitt trigger exceeds U_{on}, the trigger turns on and when the input falls below U_{off} the schmitt trigger output is 0), $h = U_{on} - U_{off}$ is the hysterisis width, $E_d = U_{on}/K_m$ is the equivalent internal deadband, and fT_{on} is the the duty cycle
From the static characteristics it can be understood unlike the PWM scheme, the minimum pulse width for PWPFM scheme is independent of thrust and inertia and is only a property of the designed modulator.To reduce the errors and rates at control off, PWPFM based control scheme also was explored for CM control. The design of PWPF Modulator was carried out for minimum pulse width of forty milli seconds. The static characteristics of modulator are plotted and given in Fig 11. Modulator parameters were selected based on static analyses and finalised through simulations.

Due to its pseudo linear characteristics, PWPFM systems are analysed like linear systems. The Describing function of PWPF modulator available in literature [Ref-10] can be made use of to derive the stability margins namely phase and gain margin. Describing function analysis was also carried out before finalising the design. The PD design numbers were tuned to maximise the margins. Typical simulation results with PWPFM control is shown in Fig 12. The control scheme results in very low rates and errors at atmospheric entry.

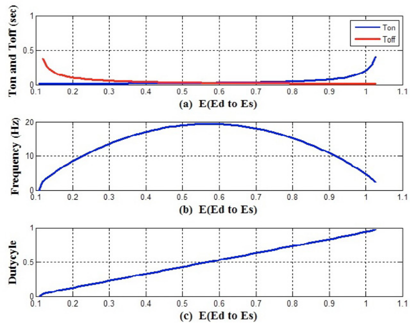

Fig. 11. Static characteristics of PWPF (a) Ton and Toff, (b) On-off frequency, (c) Duty cycle

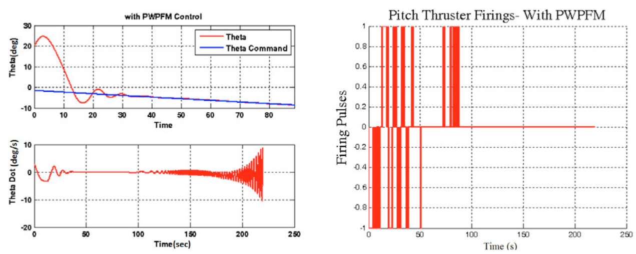

Fig. 12. Pitch Channel Control With PWPFM

5. CONCLUSION

The attitude control system design for Crew Module Atmospheric Re-entry Experiment Mission was carried out considering the mission requirements. We have investigated different modulation schemes for control of Crew Module during exo-atmospheric regime. Rates at parachute deployment are highly sensitive to re-entry initial conditions. Hence Design Parameters are tuned to ensure minimum end conditions at control OFF.To ensure the robustness of module reentry trajectory elaborate simulations were carried out. Simulations are performed in the case of extreme initial conditions, perturbations on aerodynamic coefficients and thrust/inertia dispersion to demonstrate the effectiveness of the control strategy. In all cases simulated, rates at control-OFF were less than 0.5 deg/s in P/Y/R and errors less than 0.75 deg in Pitch/Yaw Channels. During the Crew Module Atmospheric Re-entry flight also the control performance was very close match to pre-flight simulations.

ACKNOWLEDGEMENTS

The authors are grateful to the members of Human Space Flight Project, Aeronautics Entity and Control Guidance and Simulation Entity whose collaborative efforts resulted in this paper.

6. REFERENCES

(1) Cole D. Kazemba,Robert D. Braun Ian G. Clark Mark Schoenenberger, *Survey of Blunt Body Dynamic Stability in Supersonic flow*, AIAA Atmospheric Flight Mechanics Conference 13-16 August 2012, Minneapolis, Minnesota
(2) Md Shafeeq Ahmed, Vinod Kumar, Amit Sachdeva, Pankaj Priyadarshi, *Monostability characteristics of Crew Module-CFD Studies*, Symposium on Applied Aerodynamics and Design of Aerospace Vehicles (SAROD 2009) December10-12,2009, Bangalore, India.
(3) Gangbing Song, Nick V. Buck and Brij N. Agrawal-*Spacecraft Vibration Reduction Using Pulse-Width Pulse-Frequency Modulated Input Shaper*,Journal Of Guidance Control and Dynamics, Vol. 22, No. 3, MayJune 1999.
(4) Luke W. McNamara, *Entry Atmospheric Flight Control Authority Impacts on GN and C and Trajectory Performance for Orion*, AIAA Guidance, Navigation, and Control Conference 13 - 16 August 2012, Minneapolis, Minnesota.
(5) N.V.Kadam, *Flight Control Systems for Launch Vehicles and Missiles*, Allied Publishers Private Limited ,2009
(6) Dr Unnikrishnan Nair, Dr.S Ramakrishnan, K Kumar, *Unmanned flight testing of CARE module in LVM3X/CARE mission* ,9th IAA Symposium On The Future Of Space Exploration,Torino,Italy,July7-9,2015.
(7) Bong Wie, Carl T. Plesciat, *Attitude Stabilization of Flexible Spacecraft During Stationkeeping Maneuvers*, AIAA Guidance and Control Conference, Gatlinburg, Tenn., Aug. 15-17,1983.
(8) N.K. Philip, V. Chinnaponnu, E. Krishnakumar, P. Natarajan,V.K. Agrawal, N.K. Malik, *Attitude control schemes for the first recovery mission of India* ,58th International Astronautical Congress, Hyderabad, 2007.
(9) Tobin C. Anthony, Bong Wie and Stanley Carroll, *Pulse-Modulated Control Synthesis for a Flexible Spacecraft*,AIAA Guidance, Navigation, and Control Conference, 1989.
(10) Brij N. Agrawal, R.S.Mcclelland and Gangbing Song-*Attitude Control of flexible spacecraft using pulse width pulse frequency modulated thrusters*,47^{th} International Astronomical Congress,1997.

Appendix A. NOMENCLATURE

A = capsule area m^2
D = capule reference diameter , m
g = gravitational acceleration, m/s^2
h = altitude, m
V = velocity, m/s^2
R = radius of earth, m
m = crew module mass, kg
L/D =lift-to-drag ratio
ρ = atmospheric density, kg/m^3
α = angle of attack
C_L = aerodynamic lift coefficient
C_D = aerodynamic drag coefficient
CG = center of gravity
C_m = aerodynamic pitch moment coefficient
$C_{mq}, C_{m\dot{\alpha}}, C_{m\alpha}$ = aerodynamic pitch moment dynamic stability coefficients
γ = flight-path angle
θ, ψ, ϕ = Pitch/Yaw/Roll Attitude Angles
p,q,r = Roll/Pitch/Yaw Body Rates
K_A = Forward Gain
K_R = Rate Gain